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New Methods for Locating Earthquakes in southern California

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Investigations

We have worked on improving earthquake locations in southern California using a variety of different approaches. These include: (1) Application of an L1-norm, grid-search method for robustness with respect to bad data, (2) Computation of station terms to account for three-dimensional velocity structure, and (3) Use of waveform cross-correlation to improve relative event locations among nearby events.

Results

Here we summarize results from several different studies that we have completed during the last year, including Richards-Dinger and Shearer (2000), Shaw and Shearer (1999), Astiz, Shearer and Agnew (2000), Astiz and Shearer (2000), Shearer et al. (2001) and Hardebeck and Shearer (2001) to which the reader is referred for additional details.

Southern California Seismic Network Catalog

The accuracy of the earthquake locations in the Southern California Seismic Network (SCSN) catalog is limited, particularly in depth. We have found that the relative location accuracy between nearby events can be greatly improved through the use of the L1-norm and station terms. Customized station terms have often been used to improve location accuracy for individual clusters of events, and provide results comparable to master event methods by accounting for three-dimensional velocity variations between the cluster and the stations recording the events. However, such methods are not as useful for larger distributions of seismicity since a single set of station terms is not optimal for the entire seismicity volume. A practical way to relocate large areas of seismicity while achieving high relative location accuracy between nearby events is to permit spatial variations in the station terms. We have implemented this approach through an interactive procedure that first locates the events, then smoothes the residuals at each station, relocates the events, etc. We apply a smoothing algorithm based on the seismicity density that naturally increases the station term resolution in areas with large number of events.

We have relocated the SCSN catalog of over 300,000 events (1975 to 1996) by applying this approach to the existing *P* and *S* picks (Richards-Dinger and Shearer, 2000). Scatter in the locations is reduced, particularly in depth, compared to the catalog locations. This is illustrated in Figure 1 for aftershocks of the 1987 Whittier Narrows, which compares our locations with those obtained in some previous studies.

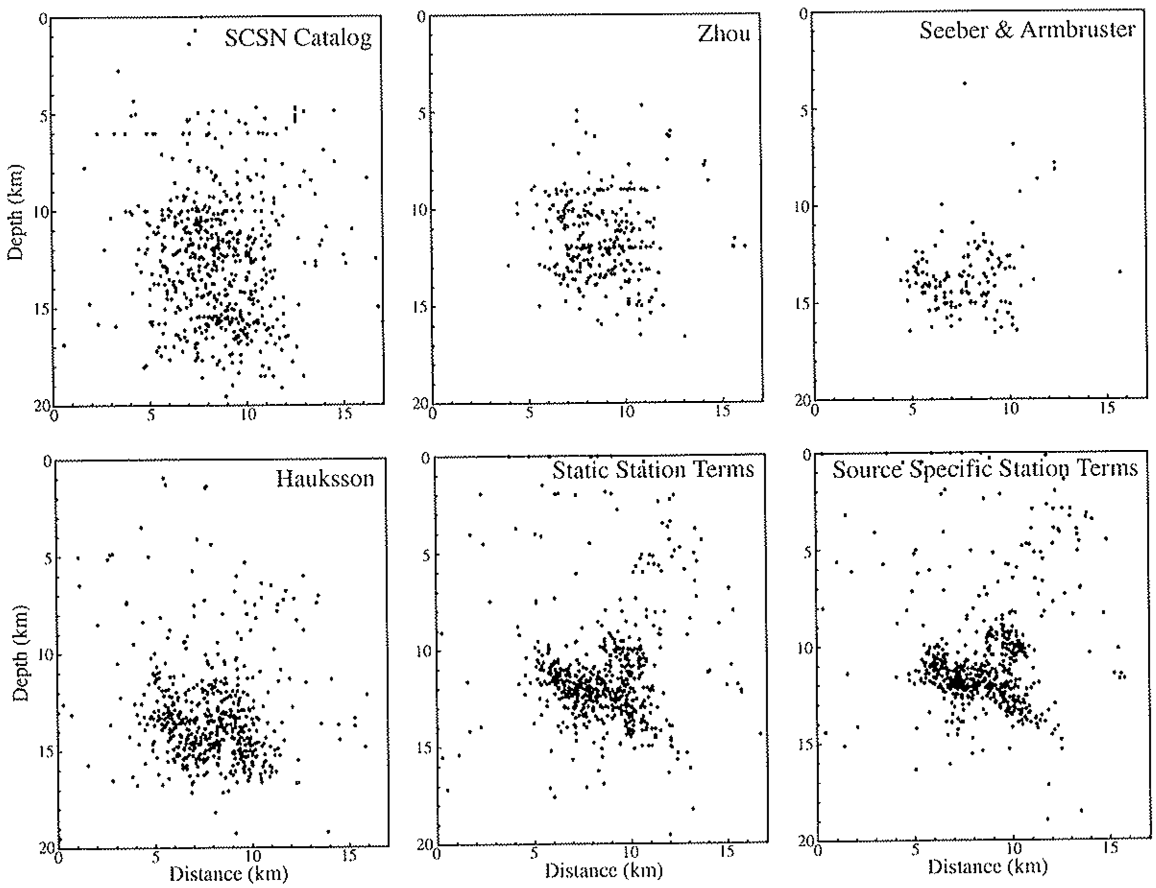

Figure 1. A south-north cross section of aftershocks of the 1987 Whittier Narrows earthquake, comparing our static station term and source-specific station term locations to those of the SCSN catalog and several other groups.

Puente Hills Thrust

Working with John Shaw at Harvard, we applied the L1-norm, waveform cross-correlation approach of Shearer (1997) to relocate the Whittier Narrows aftershocks. To improve the accuracy of the absolute event depths, we accounted for three-dimensional velocity variations in two different ways: (1) We relocated the events using station terms for SCSN stations derived from a spatially distributed set of 4800 events across southern California, (2) For four stations close to the Whittier Narrows earthquake (FLA, GVR, AC1 and TCC) we obtained detailed velocity information from boreholes. We relocated the events using the custom profiles at these stations and a reference one-dimensional model at all other stations. We forced an exact fit to the travel times for station FLA, the nearby station with the most data.

Both methods indicated that the Whittier Narrows events are shallower than the locations obtained without these corrections, which were biased downward by the slow near-surface velocities at seismic stations close to the sequence. The station term locations place the mainshock at 12.7 km depth; the borehole velocity-constrained locations place the mainshock at 13.5 km. In both cases, the mainshock locates near the center of the aftershock plane, which dips about 25° to the north. The position and orientation of the mainshock and aftershock sequence align with a fault observed in reflection seismic data 10 to 15 km south of the mainshock (Figure 2). Thus it appears likely that the M=6.0 Whittier Narrows earthquake ruptured only part of a more extensive blind-thrust fault, which we term the Puente Hills thrust, that is capable of larger and more damaging earthquakes. Due to its location beneath much of metropolitan Los Angeles, this fault is potentially very destructive.

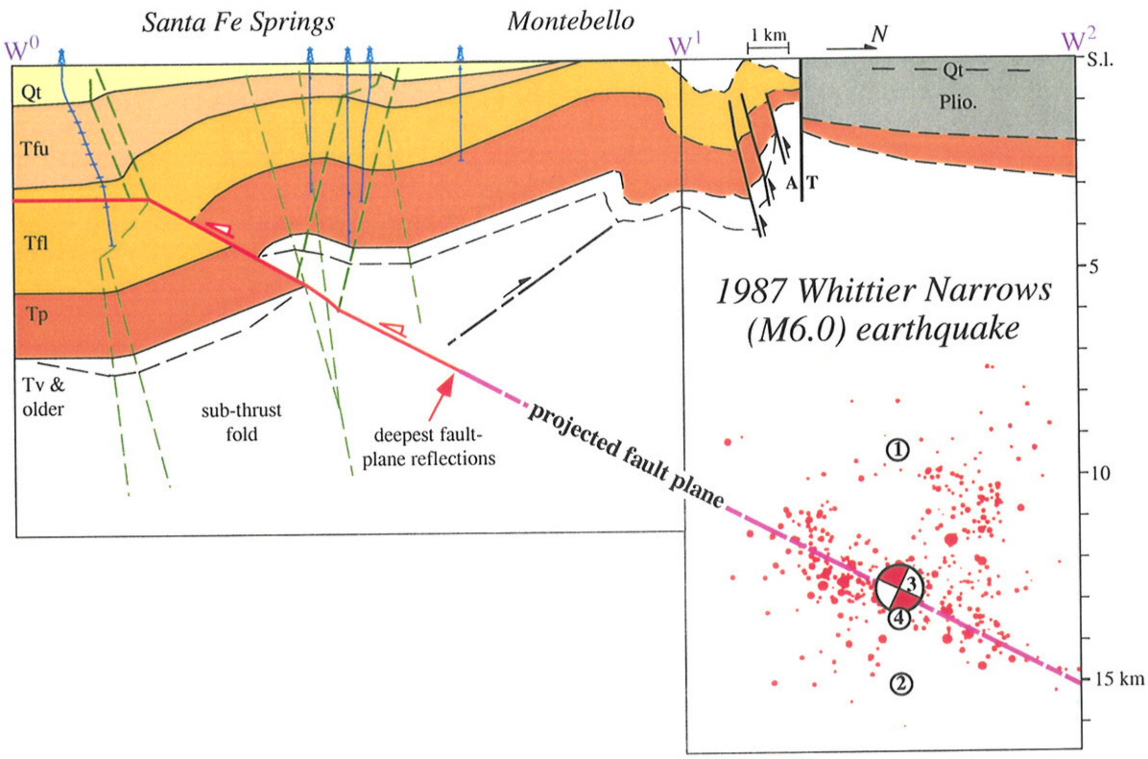

Figure 2. Geologic cross section of the Santa Fe Springs anticline and fault segment with the relocated mainshock and aftershocks of the 1987 Whittier Narrows earthquake. Note the coincidence of the relocated aftershocks with the projected fault plane.

Upland Earthquake Sequence

We relocated earthquakes that occurred near the 1988 (M = 4.7) and the 1990 (M = 5.5) Upland, California earthquakes to map the fault geometry of the poorly defined San Jose fault, and to test the static-stress-triggering hypothesis for this sequence. We adopted the L1-norm, waveform cross-correlation method of Shearer (1997) to obtain precise relocations for 1573 events between 1981 and 1997 in the Upland area. To limit computation time we only performed waveform cross-correlation on 60 of the nearest neighbors of each relocated event. Our final relocations show two linear features. The first is imaged by the locations of the initial month of aftershocks of the 1988 Upland earthquake, which delineate a fault with a dip angle of about 45° between 7 and 9 km depth, consistent with the mainshock focal mechanism. The second linear feature is a plane dipping at about 74° from 2 to 9 km depth, which is illuminated by both the 1988 and 1990 Upland sequences, in agreement with the inferred location of the San Jose fault at depth. However, below 9 km the event locations become more diffuse, giving rise to two different interpretations of the fate of the San Jose fault at depth. One possibility is that the fault shallows at depth, consistent with our relocations but not with the focal mechanism of a M = 4.7 deep aftershock. Alternatively the fault may be offset at depth by the more shallow dipping fault strand broken during the 1988 earthquake. Using these inferred fault geometries, we computed stress changes resulting from slip during the mainshocks to test whether the relocated aftershocks are consistent with the hypothesis that more aftershocks occur where the change in static Coulomb failure stress is positive (on faults optimally oriented for failure). This required an extension of previous models of changes in the failure stress to three dimensions and arbitrary fault orientation. We found that patterns of change in Coulomb failure stress differ little between the different fault geometries: all are nearly symmetric about the fault, and so do not match the aftershock distribution, in which most of the off-fault events occur to one side of the fault plane.

Continental Borderland Earthquakes

The inner Continental Borderland region, offshore southern California, is tectonically active and contains several faults that are potential seismic hazards to nearby cities. However, fault geometries in this complex region are often poorly constrained due to a lack of surface observations and uncertainties in earthquake locations and focal mechanisms. To improve the accuracy of event locations in this area, we apply new location methods to 4,312 offshore seismic events that occurred between 1981 and 1997 in seven different regions within the Borderland. The regions are defined by either temporal or spatial clustering of seismic activity in the Southern California Seismic Network (SCSN) catalog. Obtaining accurate locations for these events is difficult, due to the lack of nearby stations, the limited azimuthal coverage, and uncertainties in the velocity structure for this area. Our location procedure is based on the L-1 norm, grid search, waveform cross-correlation method of Shearer (1997), except that we use a nearest neighbor approach (Astiz *et al.*, 2000) to identify suitable event pairs for waveform cross-correlation and we explore the effect of different velocity models on the locations and associated station terms. In general, our relocated events have small estimated relative location errors and the events are more clustered than the SCSN catalog locations. A quarry on the south tip of Catalina Island provides a test of our location accuracy and suggests that, under ideal conditions, offshore events can be located to within 1 to 2 km of their true locations. Our final locations for most clusters are well correlated with known local tectonic features. We relate the 1981 Santa Barbara Island (M_L=5.3) earthquake with the Santa Cruz fault, the July 13, 1986 Oceanside (M_L=5.3) sequence with the San Diego Trough fault zone, and events near San Clemente Island with the known trace of the San Clemente fault zone. Over 3000 of the offshore events during this time period are associated with the 1986 Oceanside earthquake and its extended aftershock sequence. Our locations define a northeast-dipping fault plane for the Oceanside sequence, but in cross-section the events are scattered over a broad zone (about 4 km thick). This could either be an expression of fault complexity or location errors due to unaccounted for variations in the velocity. Events that occur near Coronado Bank in the SCSN catalog are relocated closer to the San Diego coast and suggest a shallow-angle, northeast-dipping fault plane at 10 to 15 km depth.

Northridge aftershocks

We perform waveform cross-correlation on nearly 15,000 aftershocks of the 1994 Northridge M=6.7 earthquake in southern California as recorded by short-period stations of the Southern California Seismic Network (SCSN). Approximately 10 to 30% of the events belong to similar event clusters, depending upon the similarity criteria that are applied. We relocate events within 218 of these clusters to a relative location accuracy of about 30 m using the differential times obtained from the cross-correlation. These relocated event clusters often show planar features suggestive of faults at depth and we apply principal parameter analysis to characterize the shape of each cluster and to compute best fitting planes. In several cases these planes are parallel to the mainshock fault plane; however, more generally the seismicity planes exhibit a wide range of orientations suggesting complexity in the aftershock faulting. Composite focal mechanisms can be obtained for each cluster by combining the P polarity data from individual events. A comparison of polarity measurement differences within similar event clusters provides constraints on the error rate in the individual focal mechanisms. For some clusters, we are able to resolve the primary versus auxiliary fault plane ambiguity by comparing the computed focal mechanisms with the best fitting seismicity planes. Individual event focal mechanisms are in general agreement with the composite focal mechanisms for the similar event clusters. Events occurring along the mainshock rupture plane are mainly thrust whereas events in the hanging wall are predominately strike-slip.

Non-technical summary

We have developed new techniques for locating earthquakes in southern California and used them to relocate nearly 300,000 events during the last 20 years, including several major aftershock sequences following large earthquakes. Our locations are much more accurate than the standard catalog locations and permit better delineation of fault structures in southern California.

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Data availability statement

We use arrival-time and waveform data that are readily available from the Southern California Seismic Network. Our earthquake locations are published in the open literature; in addition, we have distributed our catalog of nearly 300,000 locations via an anonymous ftp site and the SCEC data center.